ARGON FLUORIDE EXCIMER LASER SOURCE FOR SUB-0.25 mm OPTICAL LITHOGRAPHY

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ABSTRACT

The spectral characteristics of an ELS-4000 excimer laser operating at 193 nm and employing two different line-narrowing schemes have been studied. Partial bandwidth reduction (72 pm FWHM) was achieved using a single dispersive prism. The laser generated an average output power of 4 W, making it a useful source of VUV radiation for broad-band 193 nm lithography. Narrow-band operation (5.5 pm FWHM) was attained using a prism-grating combination. The maximum narrow-band energy was 6 mJ; however, the average power was low (0.6 W). Improvements in the gain generator and optics will be needed to extract higher power levels for narrow-band lithographic applications.

1. INTRODUCTION

In the last few years, tunable, spectrally narrowed KrF laser systems have been developed which are production-worthy sources of 248 nm radiation for DUV lithography [1]. More recently, research effort is shifting to the next generation of VUV laser steppers which can achieve sub-0.25 mm linewidths. The ArF excimer laser at 193 nm is a natural candidate as the VUV source, since it would be very similar to its KrF predecessor and would not present a major technological change-over to the lithographer or to the fabrication line designer.

We present here the results from a preliminary investigation into the performance of Cymer's standard KrF production laser, the ELS-4000, which has been converted to ArF operation.

Initial 193 nm lithography efforts have used either all-reflective optics, which require little or no spectral narrowing to be done on the source laser, or refractive lens designs employing various degrees of achromatization, which do require the laser source to be spectrally narrowed[4]. To cover this range of needs, the spectral characteristics of the laser were studied using resonator optics producing broadband, moderately narrowed (< 100 pm), and strongly narrowed (< 10 pm) outputs. Many of the diagnostic techniques and instrumentation used here were previously employed in an earlier study [1], although modifications to the equipment was sometimes necessary to accommodate 193 nm operation. In addition to spectral studies, other basic performance characteristics, such as beam profiles, polarization ratio, average power, etc. are given for the moderately narrowed configuration.

2. ArF GAIN GENERATOR

The laser used for this study was a Cymer ELS-4000, with all the standard 248 nm (KrF) optical packages removed. To reduce window losses for polarized output, the chamber was fitted with new window housings which held the uncoated CaF_2 windows at 45°. No other modifications were made to the chamber or to the pulse-power electronics. Optimization studies were performed to identify the optimum ArF gas mix for the system. The performance as a broadband ArF laser is as follows:

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Optics:	plane-parallel cavity, 25% output coupler, total reflector rear
Gas mixture:	2.5 t F_2, 75 t Ar, 2300 t Ne
Single shot energy	@ 16 kV: 28 mJ @ 19 kV: 50 mJ
Average power	@ 400 Hz, 16 kV: approx. 10 W

3. BROADBAND ArF SPECTRUM

The spectroscopic studies were begun by examining the endlight spectrum produced by the gain generator. With front and rear resonator optics removed, the spontaneous emission slightly off-axis was gathered by a 10 cm lens and fed via a fused silica fiber-optic bundle into a THR1500 spectrometer, which used a Hamamatsu R292 photomultiplier as a detector. In addition, the emission spectrum from a mercury hollow cathode lamp was folded into the input to the spectrometer to provide spectral calibration references. Scans of the mercury line at 194.227 nm indicated a spectrometer resolution of about 7 pm FWHM. Following normal spectroscopic convention, all wavelengths below 200 nm are reported as vacuum wavelengths.

The ArF endlight spectrum is shown in Figure 1. The solid curve is the spectrum which results after traveling through approximately 7 meters of air, and clearly shows the well-known Schumann-Runge absorption bands of molecular oxygen. Three major vibrational bands for the (B - X) transition fall within the ArF gain curve, the (3,0), (4,0), and (5,0) bands [2]. The (4,0) band is the most troubling, since it overlaps the peak of the gain curve where broadband lasing occurs. Nitrogen purging of all inter-cavity and external optical paths is necessary to avoid absorption losses, as well as to avoid ozone formation and photochemical deposition of contaminant layers on optical components from organic vapors normally present on laboratory air. The dashed curve of Figure 1 shows the spectrum when all air paths are purged with nitrogen. The spectrum extends to below 188 nm, although the amplitude is too low in this region

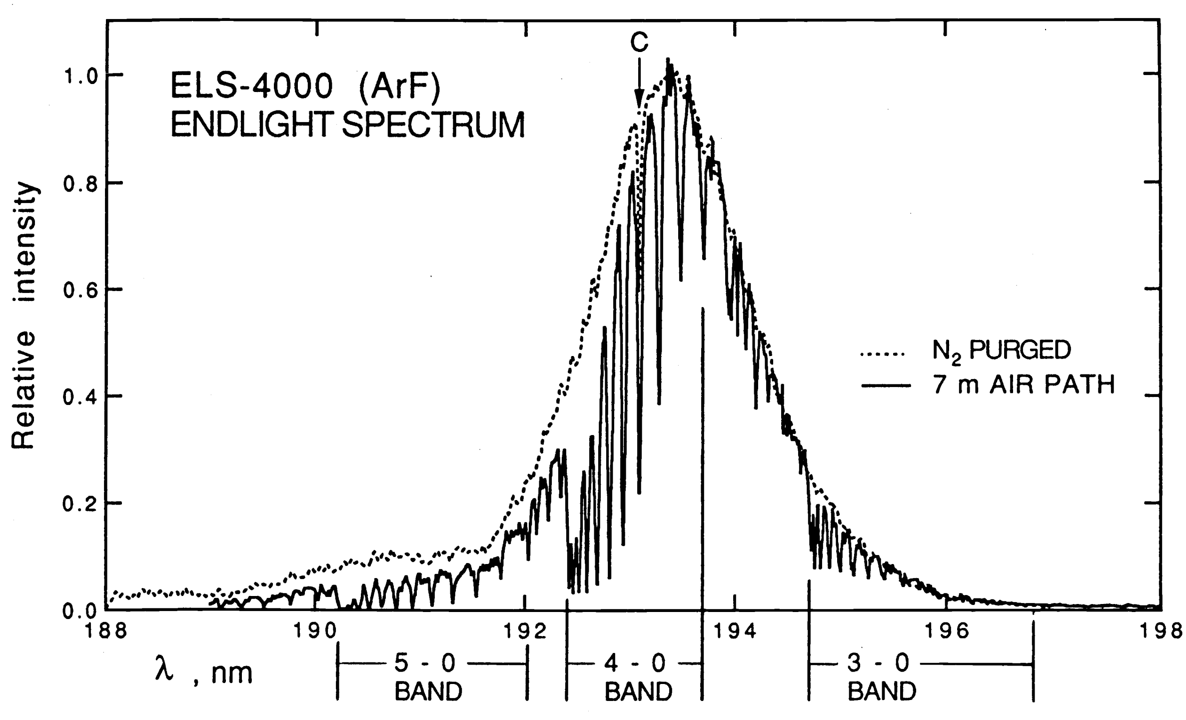


Figure 1. Endlight spectrum of the ArF laser after propagating through 7 meters of air (solid curve), and with N_2 purge (dotted curve). The (3,0), (4,0), and (5,0) Schumann-Runge bands of molecular oxygen are noted, as well as a strong carbon absorption line (C).

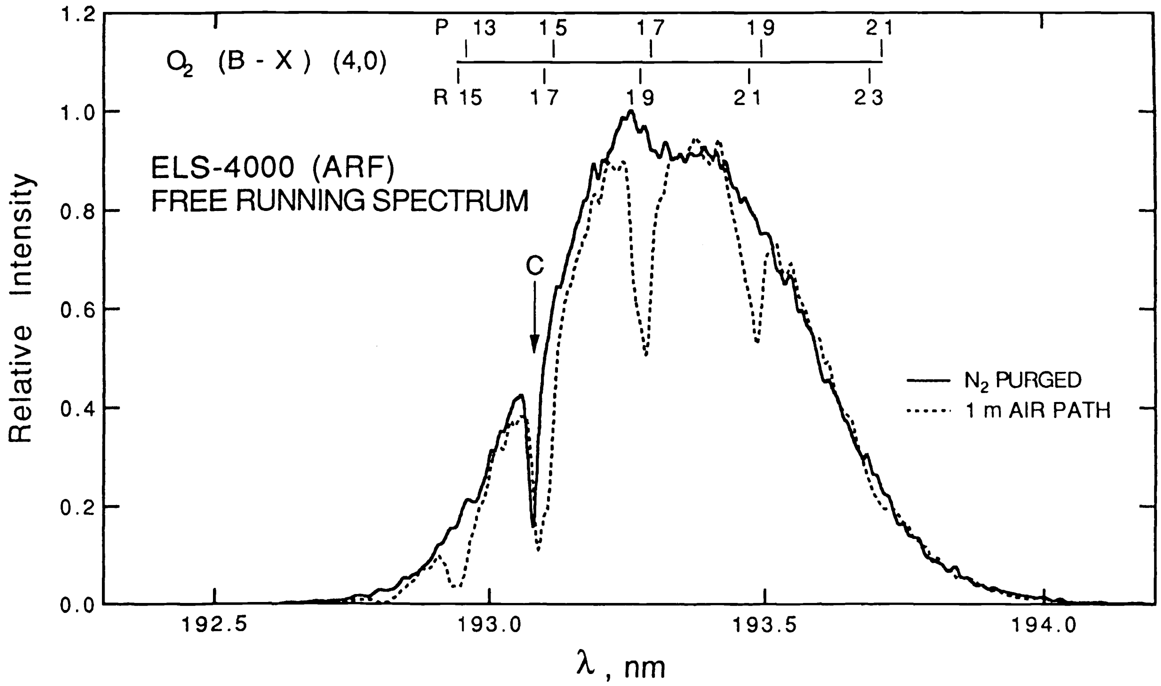


Figure 2. Spectrum of the free-running laser, after propagation through 1 meter of air (dotted curve), and with nitrogen purge (solid curve). Several P and R rotational lines of the (4,0) vibrational band of oxygen are noted, along with the carbon absorption line at 193.0905 nm. (After Burnham and Djeu [5].)

to achieve lasing threshold. Note the persistent absorption line near 193 nm. This is due to neutral carbon (193.0905 nm) and serves as a convenient spectral calibration marker. Carbon is a rather pervasive element, and can be introduced from many sources: hydrocarbon impurities in the gas supplies, elastomer O-ring seals used in chamber construction, electrode erosion, etc.

Next, the broad-band resonator optics were put into place and the free-running lasing spectrum measured, shown in Figure 2. The solid curve was obtained using nitrogen purge, and clearly shows the carbon absorption line. The free-running spectrum is about 500 pm wide, centered at 193.3 nm. Allowing the beam to propagate 1 meter in air (but with the spectrometer and intercavity optics nitrogen purged) yields the dashed curve of Figure 2. Four oxygen absorption lines appear, each one consisting of two closely spaced P and R rotational lines, and each line having a width of approximately 15 pm [2]. For reference, the wavelengths of the P and R rotational lines for the (4,0) band of O_2 are noted. Falling as it does near the P(15) (193.1135 nm) and R(17) (193.0978 nm) rotational lines, the carbon line can sometimes be mistaken for an incompletely purged system.

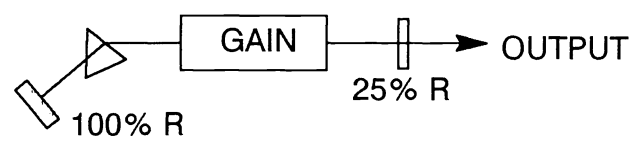
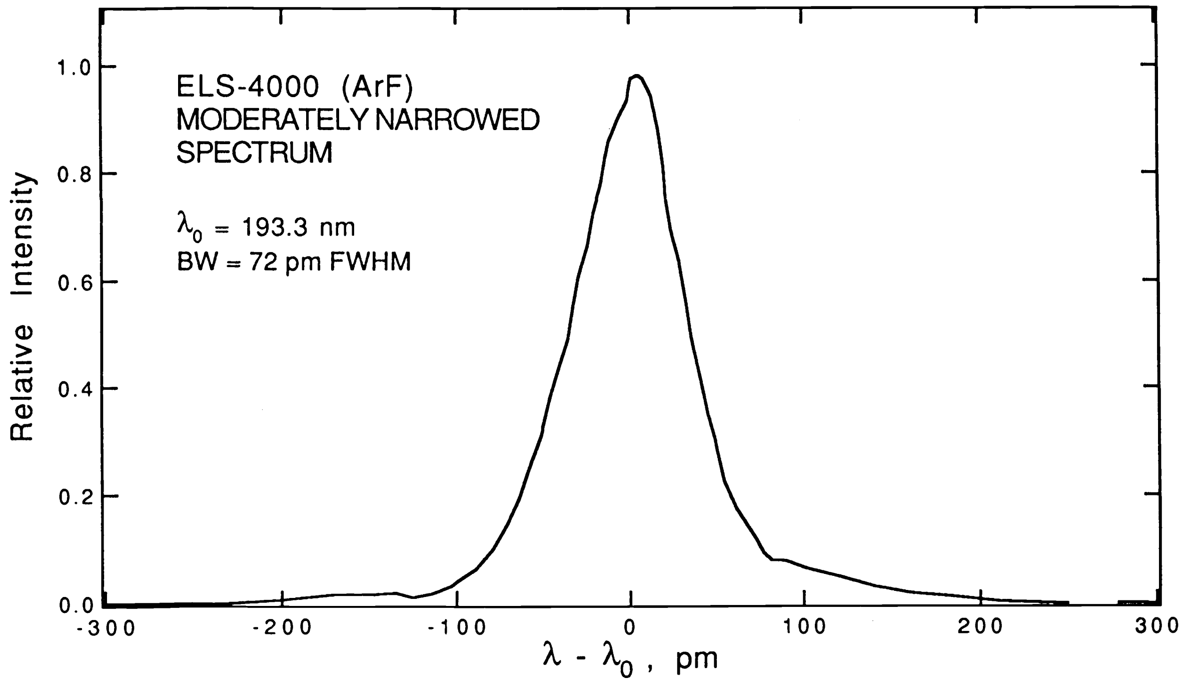
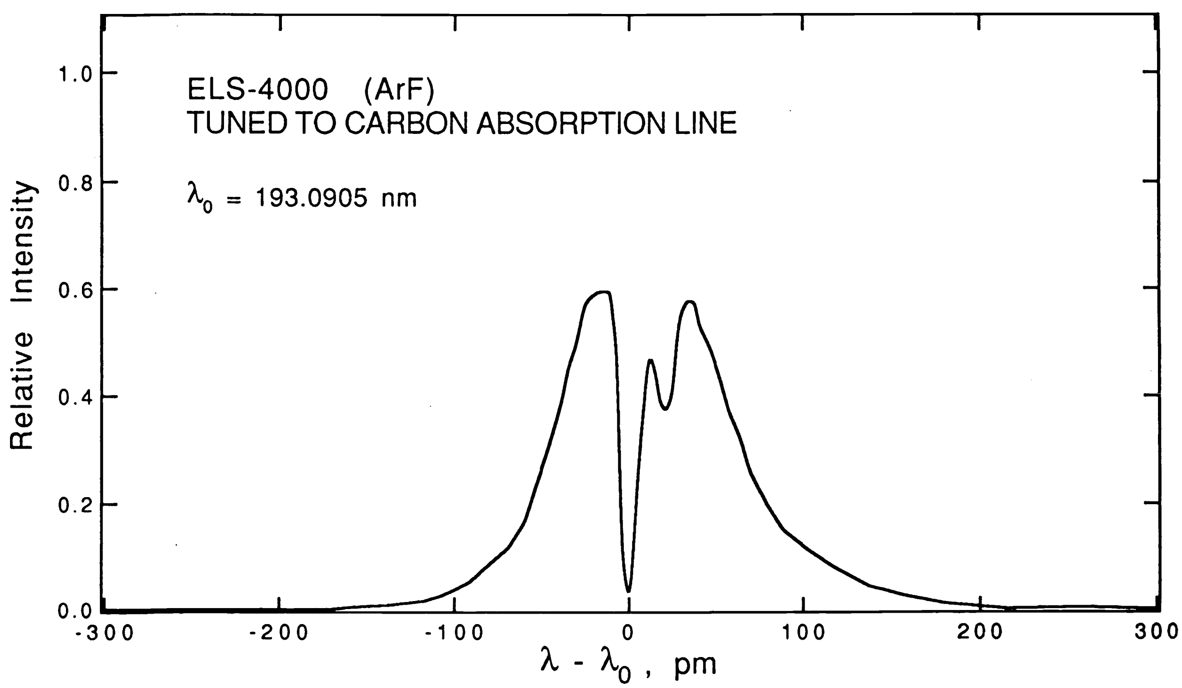


Figure 3. Prism-tuned arrangement for attaining partial bandwidth reduction of the ArF laser.





Figures 4 (a), (b). Spectrum of the partially narrowed laser with the wavelength tuned to the center of the gain curve (a), and centered on the the carbon absorption feature at 193.0905 nm (b). The bandwidth has been reduced by about a factor of seven, to 72 pm FWHM. Pulse energy is 25 mJ.

4. PARTIAL BANDWIDTH REDUCTION

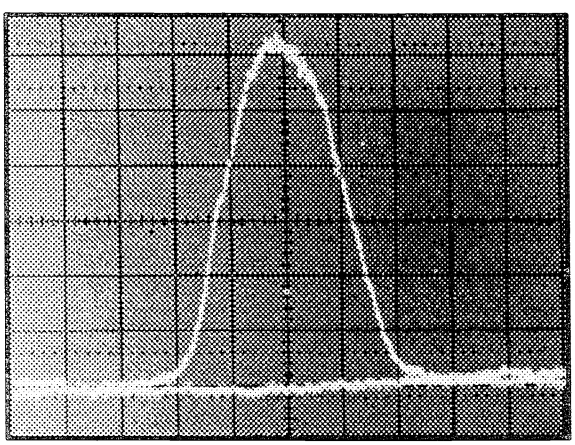
Moderate reduction in the bandwidth was achieved by the time-honored technique of introducing a single 45° fused silica prism as a dispersive element (see for example Ref.[5]), as shown schematically in Figure 3. In addition, front and rear apertures (5 and 3 mm, respectively) were added to improve spectral selection. This resonator is tunable (by scanning the total reflector) over the entire free-running bandwidth of the laser, from about 192.9 to 193.8 nm. Figure 4a shows the spectrum when tuned near the peak of the gain curve, at 193.3 nm. The spectral shape is approximately Lorentzian, with a width of 72 pm FWHM. When tuned to 193.1 nm, the spectrum develops a hole, shown in Figure 4b, caused by the carbon absorption line previously seen. The minor dip to the right of the carbon line is the (4,0) P(15) rotational line of oxygen, indicating some air contamination of the intercavity optics.

The single-pulse energy is 14 mJ at 16 kV, and 25 mJ at 19 kV, or about half of the free-running energy. These pulse energies hold up fairly well at high repetition rates: the average power, as measured by a Coherent Model 300 power meter, is 4.1 W at 400 Hz, 16 kV.

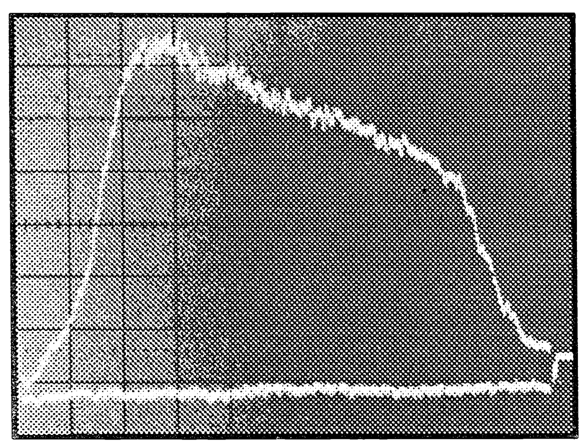
Other beam characteristics were also measured. The beam is horizontally polarized due to the polarization-selective losses from the 45° windows and the dispersive prism surfaces. Using a Brewster plate polarizer, the polarization ratio was found to be 90.3%. The optical pulse width as measured by a Hamamatsu S1722-02 PIN photodiode and a 1 GHz Tektronix 7104 oscilloscope was 15 ns FWHM. In addition, vertical and horizontal beam intensity profiles were measured at 1 meter from the laser using a 1024 element photodiode array, and are shown in Figures 5a and b. The beam shape is similar to the KrF beam profile, measuring approximately 6.2 mm wide by 18 mm tall (FWHM) along the centerlines. The vertical profile is somewhat asymmetric, with the top (cathode side) of the beam more intense than the bottom. This is a consequence of the discharge being slightly trapezoidal - narrower at the cathode than the anode. As a result, the gain is higher near the cathode. Optimization of the electrode profiles for ArF operation would be expected to improve the symmetry.

5. NARROW-BAND OPERATION

Further reduction of the spectral bandwidth requires the use of a much more highly dispersive element in the optical resonator. While some workers prefer to use etalons[4], our experience with making grating-tuned narrowband optical packages for KrF lasers prompted us to start with a grating for this effort. Initial attempts to simply modify our standard 248 nm line-narrowing optical package for 193 nm operation were unsuccessful, the increased losses at 193 nm being too great to achieve lasing threshold. Using a simpler approach, the familiar prism-grating arrangement in Figure 6 resulted in reasonable laser output. 3 mm (rear) and 5 mm (front) apertures were used, along with a 3x prism beam expander. The grating was operated in



(a)



(b)

Figures 5 (a), (b). Horizontal (a) and vertical (b) beam intensity profiles taken through beam center, 1 meter away from the laser. Horizontal scale is 2.5 mm/div.

high order to achieve the required dispersion. The entire arrangement was tented with plastic and nitrogen purged to exclude oxygen. With the laser operating at maximum voltage (19 kV), this arrangement produced 6 mJ of narrow-band light.

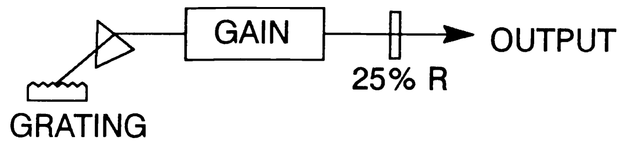


Figure 6. Prism-grating arrangement used to achieve narrow-band operation.

The spectral width was measured by a custom built, very high resolution 1 meter spectrometer which we have used previously to make measurements on our KrF lasers at 248 nm [1]. Some modifications were made to the spectrometer in order to operate at 193 nm, such as adding provisions for nitrogen purge. A 1024 element photodiode array was used as the detector in the output image plane of the spectrometer. The resolution of this system is 0.75 pm.

The spectrum of the narrow-band laser output is shown in Figure 7. The shape is Lorentzian, with a (non-deconvolved) FWHM of 5.5 pm. This shape is very typical of the spectral profiles seen on our narrow-band KrF systems. The center wavelength was tunable over the wavelength range 193.1 nm (just next to the carbon absorption hole in the gain profile) to 193.6 nm. Although not directly measured, the passive wavelength stability of the line-narrowed ArF output is expected to be comparable to the KrF design, which typically holds its wavelength (unstabilized) to within a few pm.

Attempts at running the laser at useful average powers were largely unsuccessful, due to a rapid fall-off in energy per pulse with pulse repetition rate. The highest power seen was 0.6 W, operating at 300 Hz, 19 kV. The spectral characteristics remained unchanged at high rep rate. The explanation for this is that the laser is running just barely over threshold. As the pulse repetition rate is increased, any fall-off in the intrinsic gain will have a greatly amplified effect on the output energy. For example, at 100 Hz, the endlight intensity was measured to be 95% of the 1 Hz intensity, yet the lasing output fell by more than a factor of two. Changes in the gain generator, specifically changes in the electrode geometry, will be needed to achieve higher average powers. The results of such modifications will be the subject of a future publication.

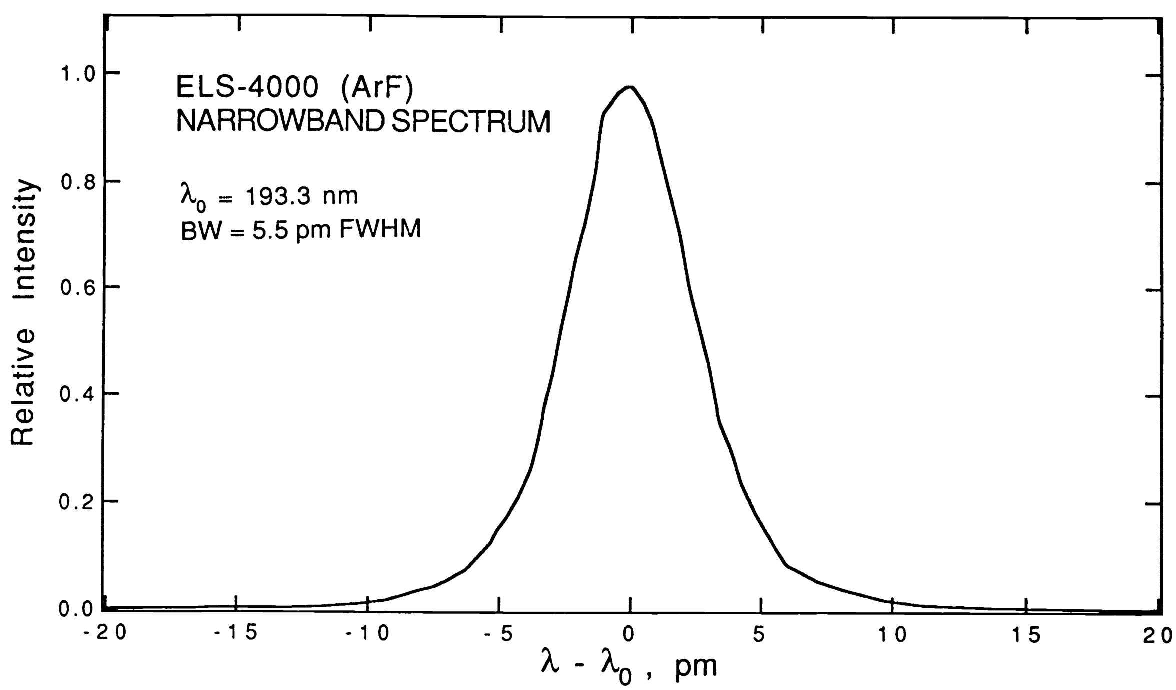


Figure 7. Narrow-band spectrum resulting from the prism-grating arrangement. The single pulse energy is 6 mJ.

6. SUMMARY/CONCLUSION

The ELS-4000 laser has been successfully converted over to operation at 193 nm. Partial bandwidth narrowing (72 pm FWHM) was achieved using a single dispersive prism. In this configuration, the laser generated an average output power of 4 W, making it a useful source of VUV radiation for broad-band 193 nm lithography. Spectroscopic studies of the gain generator revealed a hole in the ArF gain curve, caused by absorption by neutral carbon. Narrow-band operation (5.5 pm FWHM) was attained using a prism-grating combination. The maximum narrow-band energy was 6 mJ. However, improvements in the gain generator and optics will be needed to extract useful amounts of power for narrow-band lithographic applications.

References

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